Transportation Research Part D 68 (2019) 99–109

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

High airborne black carbon concentrations measured near roadways in Nairobi, Kenya

Michael J. Gatari[a], Patrick L. Kinney[b,1], Beizhan Yan[c], Elliott Sclar[d], Nicole Volavka-Close[d], Nicole S. Ngo[e,*], Samuel Mwaniki Gaita[a], Anna Law[b], Peter K. Ndiba[f], Anthony Gachanja[g], Jennifer Graeff[d], Steven N. Chillrud[c]

[a] Institute of Nuclear Science and Technology, College of Architecture and Engineering, University of Nairobi, P.O. Box 30197, G.P.O., Nairobi, Kenya
[b] Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, 722 West 168th St., New York, NY 10032, USA
[c] Lamont-Doherty Earth Observatory, Columbia University, 61 Rt 9W, Palisades, NY 10964, USA
[d] Center for Sustainable Urban Development, Earth Institute, Columbia University, 475 Riverside Drive, Suite 520, New York, NY 10115, USA
[e] Department of Planning, Public Policy, and Management, 1209 University of Oregon, Eugene, OR 97403-1209, USA
[f] Department of Civil Engineering, College of Architecture and Engineering, University of Nairobi, P. O. Box 30197, G.P.O., Nairobi, Kenya
[g] Department of Chemistry, Jomo Kenyatta University of Agriculture and Technology, P.O. Box 62000, 00200 Nairobi, Kenya

ARTICLE INFO

Keywords:
Air pollution
Black carbon
Sub-Saharan Africa
$PM_{2.5}$
Roadway emissions
Diesel
Urbanization
Transportation

ABSTRACT

Airborne black carbon (BC) particles have serious implications for human health and climate change and thus represent a prime target for mitigation policies. The sources of BC include vehicles burning diesel fuel, which are common in urban areas in low-income countries. The objective of this study was to examine the possible relationship between traffic and airborne BC concentrations near roadways in Nairobi, Kenya. We measured personal exposure levels of BC in Nairobi in a field campaign in summer 2009, and subsequently confirmed our ability to estimate BC quantitatively by conducting a co-location experiment in Nairobi in the fall of 2011. The central business district of Nairobi recorded 11-h average daytime BC concentrations in the range 20–42 $\mu g\,m^{-3}$ while the main highways feeding into Nairobi recorded BC levels of 17–79 $\mu g\,m^{-3}$. As far as we are aware, the data reported here include the highest multi-hour BC concentrations ever reported in Africa. Samples from gradient sampling showed rapid reduction of BC concentrations with distance away from traffic. The measured BC near the curbside of roadways was estimated to be in the range of 34–56% of $PM_{2.5}$, implying traffic was a dominant source of $PM_{2.5}$ emissions in Nairobi. The high concentrations of BC that we observed raises concern regarding potential health threats to workers, residents, and visitors, and highlights the need for policies to address traffic-related air pollution in Nairobi.

1. Introduction

Fine particulate matter ($PM_{2.5}$), i.e., airborne particles with an aerodynamic diameter less than 2.5 μm, can reach deep in the

* Corresponding author.
E-mail addresses: mgatari@uonbi.ac.ke (M.J. Gatari), pkinney@bu.edu, plk3@columbia.edu (P.L. Kinney), yanbz@ldeo.columbia.edu (B. Yan), sclar@ei.columbia.edu (E. Sclar), nvolavka@ei.columbia.edu (N. Volavka-Close), nngo@uoregon.edu (N.S. Ngo), mwanikigaita@yahoo.co.uk (S. Mwaniki Gaita), annagenevievelaw@gmail.com (A. Law), pkndiba@uonbi.ac.ke (P.K. Ndiba), angachanja@jkuat.ac.ke (A. Gachanja), jgraeff@ei.columbia.edu (J. Graeff), chilli@ldeo.columbia.edu (S.N. Chillrud).
[1] Now at: Dept of Environmental Health, Boston University School of Public Health, 715 Albany Street, Boston, MA 02118, USA.

https://doi.org/10.1016/j.trd.2017.10.002
Received 27 January 2017; Received in revised form 11 July 2017; Accepted 7 October 2017
Available online 21 November 2017

lungs including the bronchial passages and alveoli regions (Hinds, 1999). $PM_{2.5}$ has been shown to have negative impacts on human health at typical ambient concentrations, and evidence suggests that there are no lower limits of effect (Dockery et al., 1993; USEPA, 2012).

Urban aerosol black carbon (BC) is a major component of $PM_{2.5}$ due to the incomplete burning of fuels, where the carbon to oxygen ratio is greater than one (Seinfeld and Pandis, 1998). BC is commonly used as a tracer of incomplete combustion sources such as diesel traffic (Miguel et al., 1998; Fruin et al., 2004). The BC fraction of $PM_{2.5}$ in urban areas can be an indicator of the completeness of combustion of fuels, although the ratio can also be diluted by resuspension of windblown crustal material. In urban areas in developed countries, BC fraction can vary dramatically but with typical values of around 10% found in many urban areas. BC-containing particles are internally mixed with polycyclic aromatic hydrocarbons (PAHs) and other organic compounds (Steiner et al., 1992; Seinfeld and Pandis, 1998; Cahill et al., 2011) and are implicated in causing premature mortality due to cardiopulmonary disease and lung cancer (Pope et al., 2002, 2009; USEPA 2012; IARC, 2013; Korir et al., 2015).

The term BC is used when the determination of concentrations is carried out using an optical method, while the term elemental carbon (EC) typically indicates a thermo-optical method combined with gas chromatography such as the NIOSH 5040 method (NIOSH, 1999). Analytical challenges exist for both BC and EC methods (Cadle and Groblicki, 1982; Chow et al., 2001) resulting in the need for confirmation by comparison of the two method types through collection and analysis of co-located samples; importantly, there is not a US EPA federal reference method or equivalent, a major obstacle for setting health based standards.

Africa's BC emissions from the late 1990 s to 2007 have been estimated to be about 2.0 TG or 24% of the global emissions of 8.4 TG for that period (Bond et al., 2004; Streets et al., 2004; Wang et al., 2014). A study that excluded Southern Africa (i.e., in Western, Eastern, and Northern Africa), estimated that more than 75% of BC is emitted from the biomass combustion (mainly from Savanna fires) and only 3% from traffic (Streets et al., 2004). It has been suggested that the traffic emissions in Africa has mainly impacted air quality close to main roads (Dionisio et al., 2010) as well as in urban areas such as Nairobi, Kenya, as shown in this study. BC emissions from traffic in Africa are expected to increase significantly from 2005 to 2030, due to the rapid growth of African cities and megacities (Liousse et al., 2014). In 2030, out of an estimated 2.7 TG of total BC emission from Africa, ~0.75 TG or 28% are projected to be from traffic (Liousse et al., 2014). While these total emission estimates are well studied and appreciated for policy making in developed countries, it is not the case in developing countries. In the latter, very few air quality studies have taken place in urban centers (Gatari et al., 2009; Kinney et al., 2011; Gaita et al., 2014; Ngo et al., 2015; Zhou et al., 2013), especially close to roads and at street level where people walk and travel (see additional references in Table 2).

Economic development in Sub-Saharan Africa has catalyzed rapid growth of urban centers, with corresponding increases in traffic congestion. Nairobi is a typical example; new registrations of vehicles increased from 33,000 in 2003 to 196,000 in 2010 (KNBS, 2007 and 2011). This has resulted in a large vehicle fleet of second hand, reconditioned vehicles for which maintenance capacity in both human resources and affordability is weak. The high cost of spare parts, lack of diagnostic equipment, and low levels of technician training makes the maintenance situation even worse. Another problem is the poorly functioning and uncontrolled public transport system, which is dominated by privately owned vehicles, locally known as 'Matatus'. Initially 'Matatus' were 14-seater vans but now can be up to 25-seater minibuses (Chitere and Kibua, 2011; McCormick et al., 2016). These vehicles are mostly old, imported reconditioned vans and buses from East Asia, especially Japan. Although regulations restrict the maximum age of second hand vehicles brought into the country to 8 years, a majority of these vehicles are diesel vans much older than 8 years from a variety of manufacturers (KNBS, 2011). Matatus dominate the public transport system on urban and urban-rural roads in Kenya. Regulating them has been a major challenge to the Government since Matatus provide employment to many young adults in the region (Orero et al., 2012; McCormick et al., 2016). The social culture in Kenya has strong family (and/or extended families) ties, with a large and increasing population often traveling long distances by road to maintain its social commitments. This growing demand has impacted the number and size of on-road public transport vehicles. Thus, a range of issues including demographics, infrastructure age and maintenance, economics, and culture contribute to traffic-related air pollution in Nairobi.

In spite of these trends, little data exist on the concentrations of $PM_{2.5}$ and BC that exist in urban centers in Kenya, and on the exposures encountered by residents that spend time close to congested roads. Lacking such data, it is impossible to quantify corresponding health impacts and thus provide information in support of air quality regulations. The overall objective of this study was to apply state of the art analytical methods to characterize airborne concentrations of BC in the central business district of Nairobi Kenya.

2. Methodology

2.1. Air sampling

In July 2009, a $PM_{2.5}$ measurement study was carried out using portable air samplers in 3 sites located in the central business district (CBD) of Nairobi, two highway sites and at a rural background site (Kinney et al., 2011). Site locations are depicted in Figs. 1 and 2. The Teflon filters collected in the 2009 sampling study were archived and subsequently analyzed optically for BC. In 2011, a second study was carried out at one of the same sites as Kinney et al. (2011), with the focus of this second study on measuring and comparing results for BC and EC. The second study utilized side by side "co-location" sampling of $PM_{2.5}$ using two BGI personal samplers with size selective inlets, one with a Teflon filter and the other with a Quartz-fiber filter.

All sampling sites for the July 2009 sampling were located near curbsides of asphalt-paved roads. Fig. 1 shows the sampling sites C1, C2 and C3 in Nairobi's central business district (CBD) and site H located on a section of the main highway near the Museum roundabout on Chiromo road. Fig. 2 shows site T (which includes two locations on the Thika highway (1 m from the curbside of each

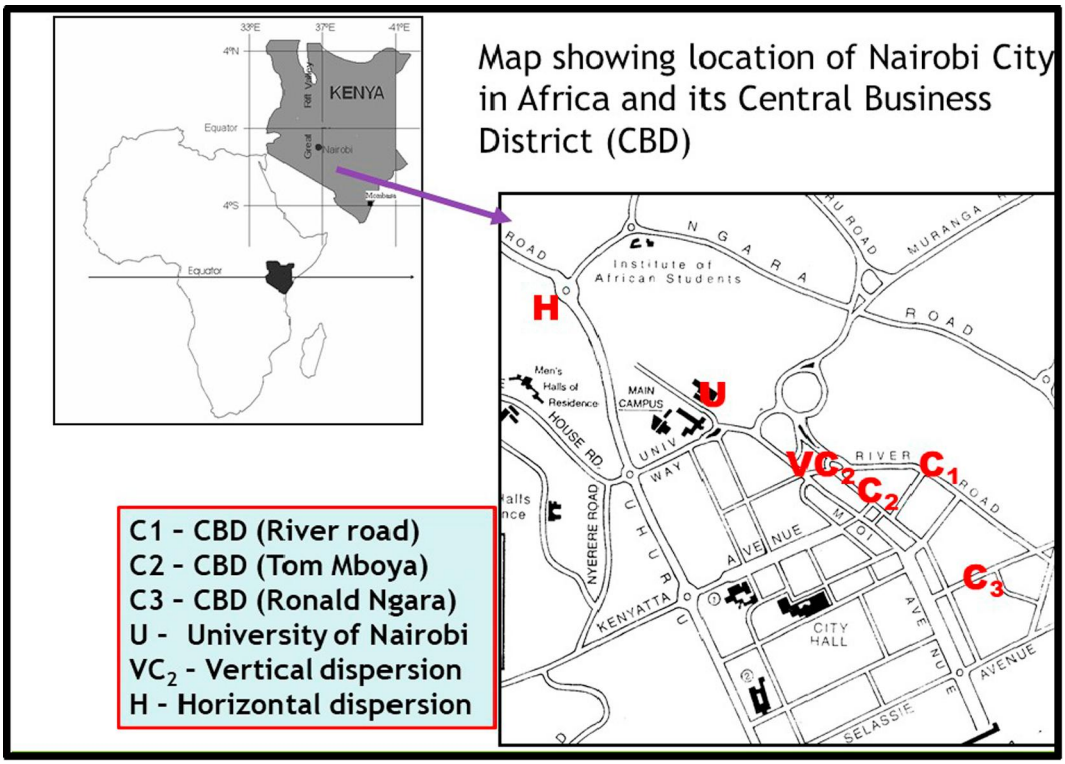

Fig. 1. Map showing the sampling sites at the Central Business District (CBD) of Nairobi during the study by Kinney et al. (2011). The site for the co-location study in October and November 2011 was at the same location as C_1 but at a slightly different height and distance from the edge of the road (see text for details).

sides of the road leading to (TIN) and away from (TON) Nairobi) and site B (a remote background site at Kenyatta University). The horizontal gradient sampling sites were at the Museum roundabout (site H). The vertical sampling sites (VC_2) were on Tom Mboya Street, next to River Road-Tom Mboya Street roundabout.

In July 2009, particle sampling was carried out from 7:30 to 18:30 on nine weekdays, a sampling period of 11 h. Pumps were carried in backpacks by field staff located at each site, with the inlet nozzle placed near the shoulder to approximate the pedestrian breathing zone at approximately 1.5 m above ground level and 0.5 m from the curbside.

The samples for the 2011 co-location study were collected at the same River Road site (C_1) as in 2009 (see Fig. 1), but with the pumps being hung over a first-floor balcony of a hired room in a hotel (Evamay Lodge (K) LTD); this resulted in the co-location samples being collected 3 m above ground level and 1 m from the edge of the curbside. The co-location study took place from 24 October to 12 November 2011. Co-location samples were for 8 h, in two periods each day: 05:00–13:00 and 14:00–22:00. A total of 42 samples were collected (21 on Teflon and 21 on Quartz filters for BC and EC analysis, respectively).

All air samples described above were collected using BGI personal samplers (BGI Inc., Waltham, MA) configured with a vacuum pump (BGI Model 400) that pulled air at 4 LPM through a cyclone with a $PM_{2.5}$ cut size (BGI's KTL cyclone) and a 37 mm Teflon/Quartz filter housed in an airtight anti-static filter cassettes. Flow rates were measured and recorded before and after each sampling event using field rotameters (SKC) that were pre-calibrated by a mass flow meter (TSI Model 4199).

2.2. Weather

During the co-location study sampling in October and November 2011, the wind direction was generally from the north and east at speeds between 0.5 and 11 m s^{-1}, with averaged temperature of 17 °C. Fig. 3 displays the wind rose for October 2011, which was nearly identical to November (data not shown). During the July 2009 study, the wind direction was generally from the south and east, at a wind speed range of 0.5–9 m s^{-1} (Fig. 4), with average temperature of 19 °C. The weather was unusually dry during both monitoring studies, making the primary difference in weather between the two sampling periods the distribution of wind directions.

2.3. BC and EC analysis

BC was analyzed on all the Teflon filters at LDEO. The analysis was carried out using a multi-wavelength reflectometer consisting of a balanced deuterium tungsten halogen light source (DH-2000-Bal), an integrating sphere (ISP-50-8-R), a customized lab-made filter holder, and a miniature fiber optic spectrometer (Ocean Optics USB4000-VIS-NIR). The light source supplied a balanced spectrum of wavelength range 210–2000 nm but the spectrometer was configured to detect the wavelength range 345–1040 nm. The

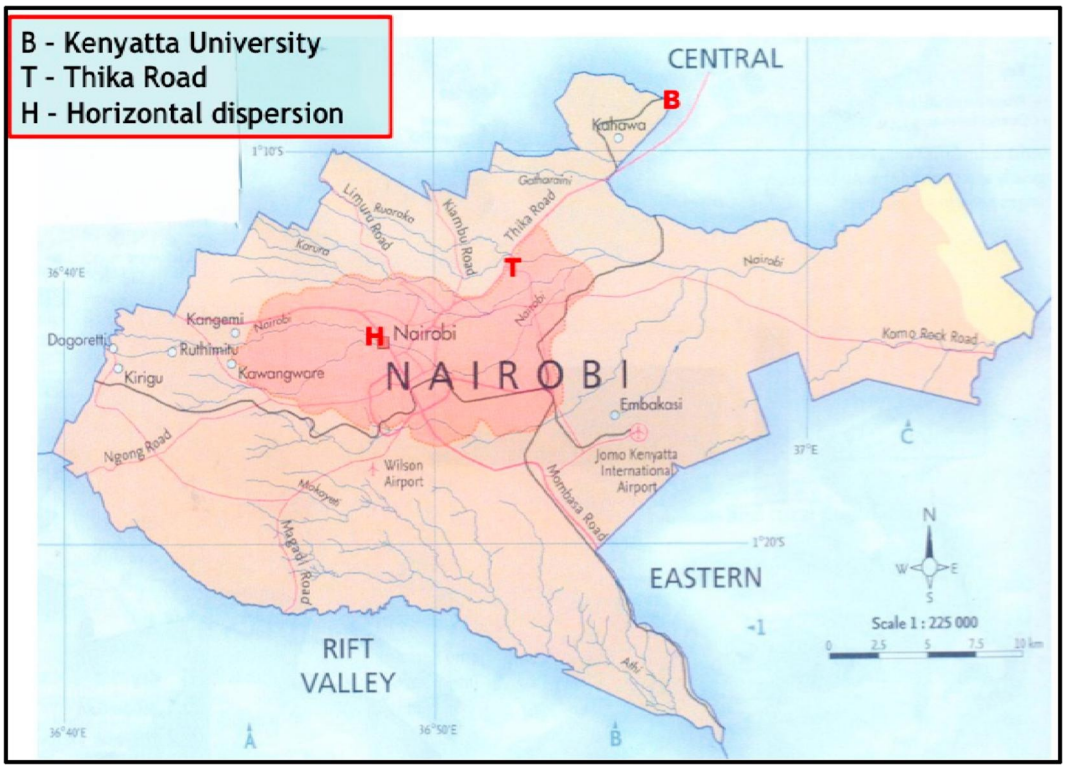

Fig. 2. Map showing sampling sites, in July 2009 (Kinney et al., 2011), which were further from the Central Business District (CBD) of Nairobi; the background site at Kenyatta University (B), Museum Roundabout (H) (later replaced by a flyover) and Thika Road (T). The map is a copy of the one purchased from Ministry of Lands, Lands office, in Kenya.

instrument validation measurements and analytical setup for BC analysis are well described in Yan et al. (2011). Importantly, this optical method has been calibrated to gravimetric BC based on kerosene soot collected onto Teflon filters after a $PM_{2.5}$ cut point cyclone in a similar way as Lawless et al. (2004). The Quartz samples from the co-location study were analyzed for elemental carbon (EC) at Sunset Laboratories (Tigard, Oregon) using NIOSH 5040 method of analysis (NIOSH, 1999). We quantified the correlation between BC and EC data from the co-location study to confirm that the optical method was valid for these samples collected in Nairobi and to allow conversion to equivalent concentration of EC for comparison to other studies.

3. Results

Comparisons of BC concentrations on Teflon filters and EC on Quartz collected in 2011 showed a strong correlation ($r = 0.93$) but with BC concentrations higher than EC by approximately 19% (Fig. 5). Thus, the measured BC values need to be divided by a factor of 1.19 to make them comparable to samples measured for EC using the NIOSH 5040 method of analysis. The overall consistency in results for BC and EC confirms the high levels measured and implies that Teflon filters were not over saturated and can be used for ambient sampling of BC content using the simple reflectance method of analysis. Reflectance analyses on Teflon filters are quicker and less expensive than the thermal optical method used for EC determination and provides a filter that can be used for metal analyses. The high correlation we observed gave us confidence to carry out optical analysis of BC concentrations from the archived $PM_{2.5}$ Teflon filter samples from the 2009 study by Kinney et al. (2011). Fig. 6 is a scatter plot of BC against $PM_{2.5}$ from that study, showing a high correlation between the concentrations ($r = 0.82$) and with a mean BC fraction of 38% as indicated from the slope.

Very high BC concentrations were observed at the street-level roadway sites (Table 1), in the CBD (sites C_1, C_2, and C_3), the street-level monitor (VC_2) at the vertical gradient site, and the Thika Highway sites (TON & TIN). Average concentrations over the nine days ranged from 30 ± 3 to 53 ± 3 $\mu g\,m^{-3}$ at those sites, with daily concentrations ranging from 17 to 56 $\mu g\,m^{-3}$. A far lower mean concentration of 3.2 ± 1.1 $\mu g\,m^{-3}$ was observed at the Kenyatta University rural site (B). Within the CBD, the street level measurements at the vertical gradient sampling site on Tom Mboya Street (VC_2), recorded the highest concentration of 56 $\mu g\,m^{-3}$ and a mean of 53 ± 3 $\mu g\,m^{-3}$. The site was next to a busy Matatu pickup and drop point.

BC concentrations decreased with respect to height above the busy street at the vertical gradient site, from 53 ± 3 $\mu g\,m^{-3}$ to 23 ± 4 $\mu g\,m^{-3}$, a 43 ± 9% drop. At the same time the samples exhibited an increase in mean BC fraction (i.e., BC to $PM_{2.5}$ ratio) from 44% to 53% with most of the increase in BC fraction from the street level to the first floor (Table 2).

Concentrations of BC immediately downwind of the 3-lane Museum roundabout (H) were the highest of any site, with a 4-day average of 72 ± 14 $\mu g\,m^{-3}$ (Table 1). This roundabout connected to a highway connecting from the Mombasa busy seaport on the

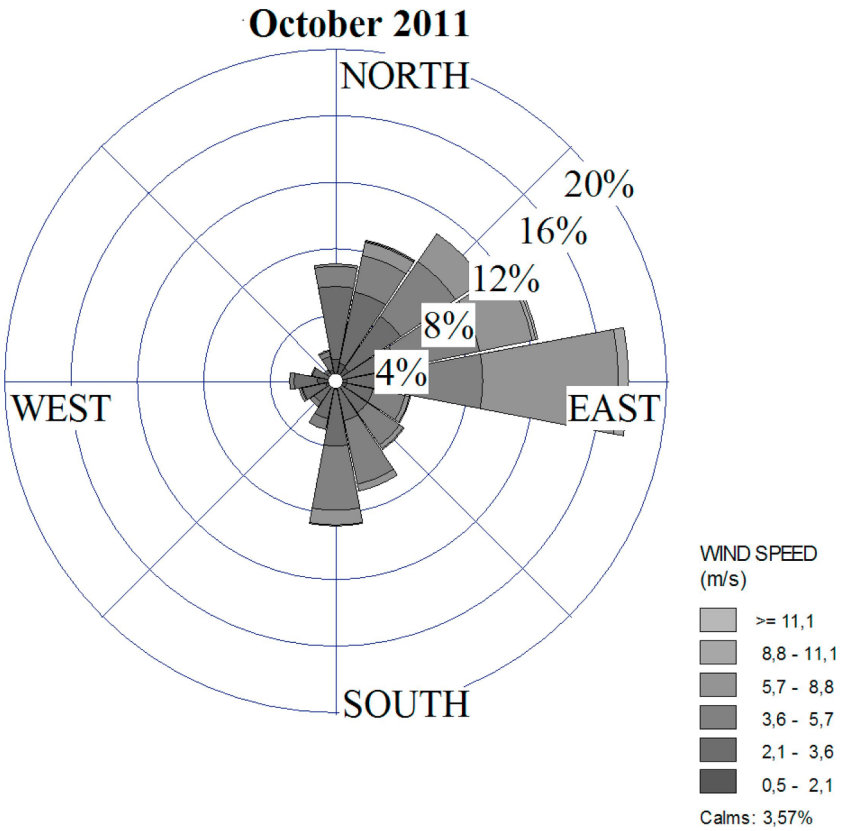

Fig. 3. Wind Rose plots displaying wind speed, direction and frequency during the co-location sampling in October 2011. Data for wind direction and speed were very similar for Nov 2011 (data not shown).

Coast of Kenya to the landlocked Uganda, Rwanda, Eastern Congo and Southern Sudan. It had many long haul diesel trucks and buses, a high concentration of local and long distance Matatus, and it frequently suffered long hours of traffic jams. Furthermore, the roundabout was at the beginning of a climb necessitating continuous accelerations and gear changes, which would also increase smoke emissions. At a distance of 30 m downwind, the average concentration was reduced to 16 ± 4 $\mu g\,m^{-3}$, followed by a reduction to 9.6 ± 1.7 $\mu g\,m^{-3}$ at 100 m. These downwind sampling points extended into an open sports fields of the University of Nairobi, where there were no other traffic sources besides the upwind rotary traffic. Concentrations were lower on Thika Highway sites (TON & TIN), which also carried heavy traffic, but with less congestion and gear changes than at the roundabout site.

Table 2 shows average concentrations of BC and $PM_{2.5}$ at all the monitoring sites, and the BC fraction in percent. The rural background site (B) had the lowest mean BC fraction of 29%. Intermediate ratios, ranging from 34% to 39%, were observed at the curbsides in the CBD. Higher ratios, ranging from 43% to 57%, were observed on Thika Highway (T) and at the vertical (VC_2) and horizontal (H) gradient sampling sites. At the latter sites (VC_2 and H), there were high vehicle densities but low speeds, which may have reduced the generation of re-suspended road dust particles, and less re-suspended dust is consistent with higher BC to $PM_{2.5}$ ratio. To allow comparison to other urban studies in Africa which sometimes measured EC, we also present the data in equivalent EC ($EC^* = BC/1.19$, where the conversion is based on Fig. 5). For each of the studies from other African cities, we selected the site(s) that was(were) most impacted by traffic in urban areas in an attempt to make the comparisons more relevant. The Nairobi curbside samples were all much higher in BC and BC fraction (and EC or EC fraction) than any of the other studies.

For the samples collected in 2011 near the River Road site (C_1), Table 3 shows the BC and $PM_{2.5}$ concentrations from the Teflon filters and the EC concentration from each co-located quartz filter.

4. Discussion

Our observations indicated very high BC concentrations in $PM_{2.5}$ samples collected in 2009 in Nairobi, Kenya, which was confirmed by high concentrations of both BC and EC from the co-located samples in 2011 (Table 3) and the strong correlation between the two (Fig. 5, r = 0.93). BC-bearing $PM_{2.5}$ particle sources can include emissions from traffic, biomass and agricultural burning, waste burning and heavy-duty diesel burning boilers, generators, and thermal electric power plants. While many of these anthropogenic source activities are present in Nairobi and may have influenced the measured BC concentrations, traffic is the primary BC source that is prevalent at street-level in the CBD and consistent with the vertical and horizontal gradient measurements. The overall importance of incomplete combustion sources to the $PM_{2.5}$ composition in Nairobi can be seen from the positive correlations between

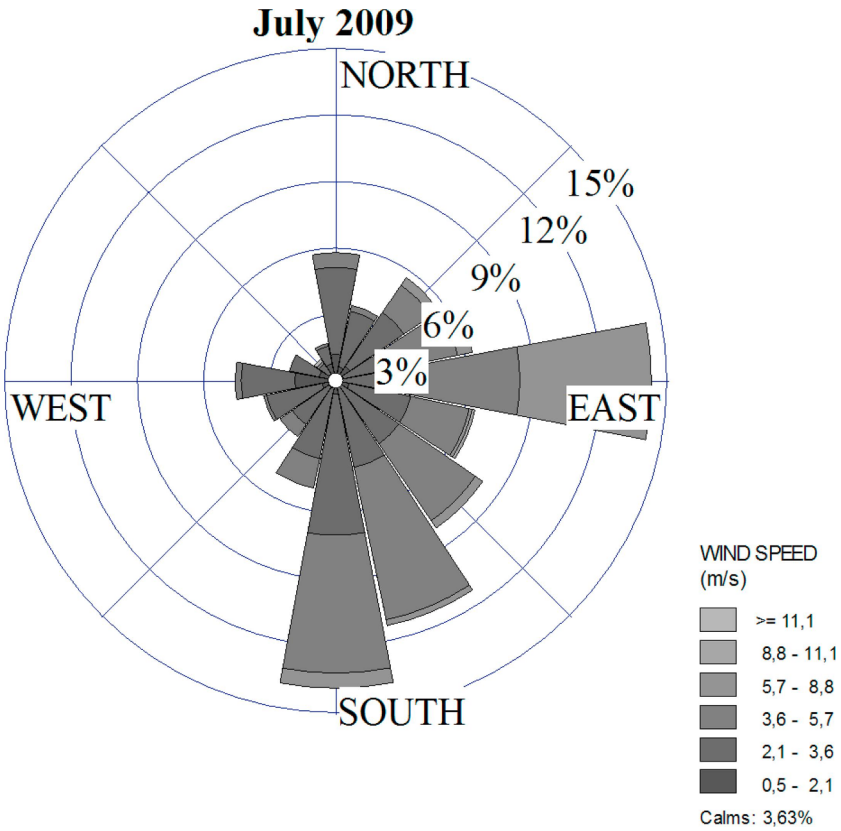

Fig. 4. Wind Rose plots displaying wind speed, direction, and frequency during the month of July 2009 sampling by Kinney et al. (2011).

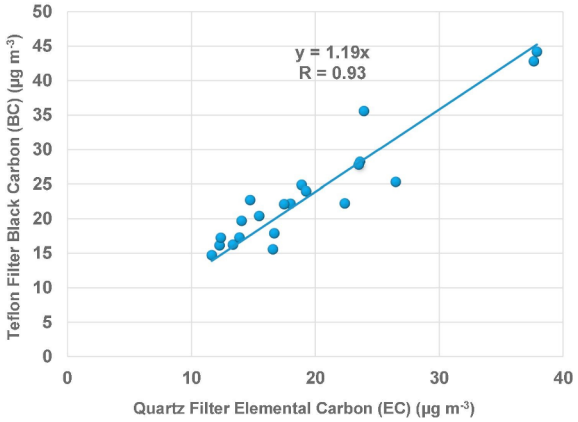

Fig. 5. Black Carbon (BC) vs Elemental Carbon (EC). BC was from Teflon filters samples analyzed by reflectance method (Yan et al., 2011) and EC from Quartz filters analyzed by NIOSH 5040 method of analyses. The filters were sampled during the co-location study in October and November 2011. The similarity in results of the two methods with a positive correlation (r = 0.93) and slope near 1.0 confirms that the high concentrations measured in Nairobi are valid. As an additional quality assessment statistic the prediction of standard error for BC is equal to 2.96 µg m^{-3}.

BC and $PM_{2.5}$ (Fig. 6, r = 0.82) and the large fraction of the total $PM_{2.5}$ being BC particles (38% on average from slope of Fig. 6). This high and variable fraction (Table 3) implies that BC is an important contributor to $PM_{2.5}$ concentrations in Nairobi and suggests a high level of incomplete combustion, consistent with Nairobi's large fleet of old diesel vehicles that are poorly maintained. Traffic emitted particles contain direct tailpipe emissions, emissions from tire and brake wear, and re-suspended road dust. Despite the presence of multiple sources of BC in Nairobi, the proximity of sampling sites in 2009 to on-road vehicles, and the decrease in BC with distance away from roadways, strongly implicates motor vehicles, especially in the CBD, as the primary source of the sampled high particulate BC. Although it proved impractical to obtain reliable data on the number and type of vehicles traversing the sampling sites, we note that the number of diesel vehicles registered between 2008 and 2010 (KNBS, 2011) was 63% of all vehicle registrations.

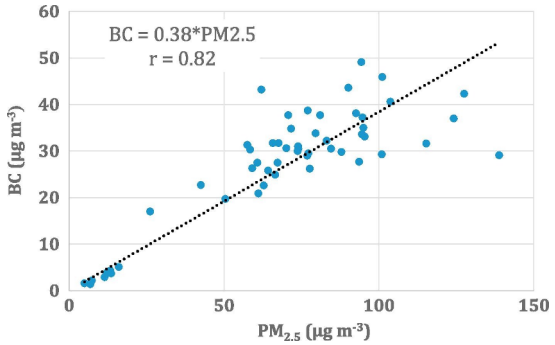

Fig. 6. Black Carbon (BC) Vs $PM_{2.5}$ analyzed from 2009 Teflon filter samples from measurement sites C1, C2, C3, TON and TIN (see text). The positive correlation (r = 0.82) and high fraction of BC in $PM_{2.5}$ (ave implied from slope of 38%, with max over 50%) indicates the strong impact of sources of incomplete combustion on $PM_{2.5}$ composition at these street-side sites in Nairobi.

Table 1
BC concentrations on Teflon filters, in μg m^{-3}, for 2009 samples, with uncertainties expressed by the standard deviation. agl = above ground level.

Location	July 6 (μg m^{-3})	July 7 (μg m^{-3})	July 8 (μg m^{-3})	July 9 (μg m^{-3})	July 10 (μg m^{-3})	July 13 (μg m^{-3})	July 14 (μg m^{-3})	July 15 (μg m^{-3})	July 16 (μg m^{-3})	Mean ± SD (μg m^{-3})
Roadway sites:										
Ronald Ngala (C_3)	31	26	31	34	28	26	20	38	32	30 ± 5
River Road (C_1)	32	29	32	31	25	28	26	32	31	30 ± 3
Tom Mboya (C_2)	35	42	37	37	41	30	29	38	35	36 ± 4
Thika Road (T) In (TIN)	38	49	20	17	28	43	30	31	23	31 ± 11
Thika Road Out (TON)	34	46	38	32	30	29	30	23	44	34 ± 7
Non-urban background site (B):										
Kenyatta Univ. (B)	2.4	3.6	3.6	1.2	2.4	4.8	3.6	3.6		3.2 ± 1.1
Vertical gradient site (VC_2):										
Street (~1.2 m agl)					52	56		50		53 ± 3
1 st floor (~4 m agl)					41	43		36		40 ± 4
3rd floor (~10 m agl)					26	31		28		28 ± 2
Roof (~17 m agl)					18	26		24		23 ± 4
Horizontal gradient site (H):										
Upwind		25		19			32		29	26 ± 6
At 0 m		79		78			50		79	72 ± 14
Downwind 30 m		14		19			12		19	16 ± 4
Downwind 100 m		9.6		11			7.2		11	10 ± 2

Concentrations of BC were highest on curbsides immediately adjacent to roads with heavy diesel traffic and decreased in the vertical and horizontal directions away from the traffic source. High curbside concentrations imply elevated exposures for pedestrians, street hawkers, vehicle drivers, travelers, and shopkeepers. However, the sample at the highest vertical distance from the curbside in the CBD still had high concentrations of BC by international standards, and compared to previously reported rooftop levels in Nairobi (Gatari et al., 2009, 2010) and Accra Ghana (Arku et al., 2008). This translated to possible roadway emissions impacting office workers in upper level offices in high buildings.

The drop in concentrations with distance from the source likely reflected a variety of loss mechanisms, including dilution, coagulation and deposition through gravitational settling and diffusion. High temperature sourced BC particles undergo rapid agglomeration (Kocbach et al., 2006) and as the particles increase in size the BC value can be seen to decrease (Cahill et al., 2011). The particle growth due to coagulation increases gravitational settling, which can be an important loss mechanism. However it is not known to what extent this process may have operated at the scale of our horizontal and vertical gradient sites. Furthermore, the BC fraction can be impacted by re-suspended crustal material present in $PM_{2.5}$ and thus by relative differences in settling of crustal material vs. combustion BC. Our study was unique in placing monitors near roadways using personal sampling equipment. Previous studies of BC in the Nairobi metro area, carried out at higher elevations and/or outside the CBD, generally reported lower concentrations, mostly below 15 μg m^{-3} (Gaita et al. (2014); Gatari and Boman, 2003; Gatari et al., 2009, 2010). Those studies were carried out in areas with relatively low traffic and reported 24 h averaged concentrations. Our 11-h daytime samples at curbside in the CBD provide data that may be more relevant for characterizing exposures of people working and going about daytime activities in those locations. The continued high concentrations seen during the co-location experiment in 2011 confirms the on-going nature of these high BC exposures in Nairobi's CBD.

At the curbside urban sites, we found that $PM_{2.5}$ mass contained a relatively high fraction of BC, ranging from 34% to 56%. A previous study with a similar sampling design of $PM_{2.5}$ in a heavy diesel traffic setting in New York City reported BC fractions ranging

Table 2
BC and $PM_{2.5}$ concentrations and ratios by site in Teflon Filter samples collected in 2009 as described in Kinney et al. (2011). We have also converted the BC data measurements to equivalent EC measurements or EC* (based on the relationship observed in Fig. 5) to allow for comparisons to chosen data from other studies in African cities that measured either BC or EC, focusing on sites described as being impacted by traffic; the original works showed other types of sites were less impacted by BC or EC than the traffic impacted sites being highlighted here.

Location and sampling period	BC (mean ± SD) (μg/mˆ3)	EC*(mean ± SD) "= BC/1.19"	$PM_{2.5}$ (mean ± SD) (μg/mˆ3)	$BC/PM_{2.5}$ %	$EC^*/PM_{2.5}$ %
This Study Nairobi, Kenya for daytime hrs in July 2009 (see text for more sampling details)					
Roadway sites:					
Ronal Ngala (C3)	30 ± 5	25 ± 4	76 ± 14	39%	33%
River Road (C1)	30 ± 3	25 ± 2	89 ± 24	34%	28%
Tom Mboya (C2)	36 ± 4	30 ± 4	98 ± 19	37%	31%
Thika Road (T) Inbound (TIN)	31 ± 11	26 ± 9	58 ± 19	53%	45%
Thika Road (T) Outbound (TON)	34 ± 7	29 ± 6	79 ± 12	43%	37%
Non-urban background site (B):					
Kenyatta Univ (B)	3.2 ± 1.1	2.6 ± 0.9	11 ± 4	29%	24%
Vertical gradient site (VC2)					
Street-level	53 ± 3	44 ± 3	120 ± 19	44%	37%
1 st floor	40 ± 4	34 ± 3	76 ± 8	53%	45%
3rd floor	28 ± 2	24 ± 2	57 ± 10	49%	42%
Roof	23 ± 4	19 ± 4	43 ± 8	53%	44%
Horizontal gradient site (H)					
Upwind	26 ± 6	22 ± 5	51 ± 10	51%	43%
Downwind 0 m	72 ± 14	60 ± 12	129 ± 21	56%	47%
Downwind 30 m	16 ± 4	14 ± 3	28 ± 3	57%	50%
Downwind 100 m	9.6 ± 1.7	8.1 ± 1.4	19 ± 3	51%	43%
	BC (mean) (μg/mˆ3)	EC (mean) (μg/mˆ3)	$PM_{2.5}$ (mean) (μg/mˆ3)	$BC/PM_{2.5}$ %	$EC/PM_{2.5}$ %
Cairo, Egypt (Abu-Allaban et al., 2007): 24 h samples					
El-Qualaly (Traffic site: Winter 1999)		13	84.6		15%
El-Qualaly (Traffic site: Fall 1999)		22.1	135		16%
El-Qualaly (Traffic site: Summer 2002)		16.3	59.3		27%
Accra, Ghana (Arku et al., 2008): 24 h samples from single site in Jun 2006					
NMT (traffic site/Nima)		2.88	26.6		11%
Ouagadougou, Burkina Faso (Boman et al., 2009): 24 h samples collected over a 2wk period in Nov-Dec 2007					
City Center Site	4.9		86	6%	
Kwabenya, near Accra, Ghana (Aboh et al., 2009) 24 h samples collected between 19th February 2006 and 15th February 2007					
	1.7		22.9	7%	
Dar es Salim, Tanzania (Mkoma et al., 2010): average of daytime and nightime samples collected at kurbside but 10 m height					
2005 Dry Season		3.6	26		14%
2006 Wet Season		4.0	19		21%
Dakar, Senegal (Doumbia et al., 2012): near crossroads at main market; real time aethalometer daytime 11 h mean estimated from Fig. 4					
Traffic site Nov. 2008 (min – max)	10–50		not measured		
Bamako. Mali (Doumbia et al., 2012): near cross roads at main market; real time aethalometer day time 11 h mean estimated from Fig. 6					
Traffic site on market days in April 2008	10–30		not measured		
Yaounde, Camaroon (Doumbia et al., 2012): near crossroads of town: real time aethalometer day time 11 h mean estimated from Fig. 6					
Traffic site 1 (June-2004)	3		not measured		
			not measured		
Accra, Ghana (Zhou et al., 2013): 48 h samples from 5 traffic sites; mean of non-harmattan impacted samples collected in 2007					
AD	6.6		27	24%	
EL	3.7		23	16%	
JT	8.6		50	17%	
NM-1	5.2		28	19%	
NM-2	6.2		34	18%	
Ouagadougou, Burkina Faso (Boman et al., 2013): 24 h samples between 29 November and 11 December 2007					
Urban (city center) site	4.9		86	5.7%	
Bafoussam, Cameroon (Antonel and Chowdhury, 2014): 24 h samples; 12 m in height and 10 m from main highway					
		3.1 ± 0.4	79		3.9%
Bamenda, Cameroon (Antonel and Chowdhury, 2014): 24 h samples; 9 m in height and 10 m from street and 1 km from main road					
		3.6 ± 1.6	124		2.9%
Yaounde, Cameroon (Antonel and Chowdhury, 2014): 24 h samples; 9 m in height and 5 m from alley way and 2 blocks from highway					
		5.5 ± 1.1	46		12%

Table 3
Results of the Teflon and Quartz filters of the co-location experiment where samples were collected near site C1 in October and November 2011 (see text), with each sample was collected over 8 h at an average flow rate of 3.925 LPM. AM indicates that sampling took place from 0500 to 1300 h, PM = from 1400 to 1600 h, and MID represented midday from 0800 to 1600 h.

Sampling date	Teflon filter ID	BC ($\mu g\,m^{-3}$)	$PM_{2.5}$ ($\mu g\,m^{-3}$)	$BC/PM_{2.5}$ (%)	Quartz filter ID	EC ($\mu g\,m^{-3}$)	$EC/PM_{2.5}$ (%)
25-Oct-11 AM	CHI1321	28	57	50%	CHQ1321	24	42%
25-Oct-11 PM	CHI1322	36	69	51%	CHQ1322	24	35%
10/26/2011 MID	CHI1323	15	47	32%	CHQ1323	12	25%
27-Oct-11 AM	CHI1324	25	57	43%	CHQ1324	19	33%
27-Oct-11 PM	CHI1325	28	81	34%	CHQ1325	24	29%
28-Oct-11 AM	CHI1326	24	43	56%	CHQ1326	19	45%
28-Oct-11 PM	CHI1327	22	37	60%	CHQ1327	18	49%
10/29/2011 MID	CHI1328	20	61	33%	CHQ1328	15	25%
10/30/2011 MID	CHI1329	22	60	37%	CHQ1329	17	29%
31-Oct-11 AM	CHI1330	22	49	46%	CHQ1330	22	46%
31-Oct-11 PM	CHI1331	25	63	40%	CHQ1331	26	42%
11/1/2011 MID	CHI1332	16	62	26%	CHQ1332	13	21%
11/2/2011 MID	CHI1333	16	78	21%	CHQ1333	12	16%
03-Nov-11 AM	CHI1334	17	42	41%	CHQ1334	14	33%
03-Nov-11 PM	CHI1335	43	100	43%	CHQ1335	38	38%
11/4/2011 MID	CHI1336	44	100	44%	CHQ1336	38	38%
11/7/2011 MID	CHI1337	23	202	11%	CHQ1337	15	7%
11/8/2011 MID	CHI1338	16	61	25%	CHQ1338	17	27%
11/9/2011 MID	CHI1339	17	73	24%	CHQ1339	12	17%
11/10/2011 MID	CHI1340	18	74	24%	CHQ1340	17	22%
11/11/2011 MID	CHI1341	20	90	22%	CHQ1341	14	16%
Mean		24	72	36%		20	30%
Stdev		8	35	13%		7	11%

from 20 to 28%, vs. 13 to 16% at sites less impacted by nearby truck traffic (Lena et al., 2002). Several studies in other African cities that have reported either BC or EC concentrations have typically included 1 or more sites that were described as being heavily impacted by traffic. However, these sites had lower BC (or EC) concentrations and lower BC fractions (or EC fractions) than the data reported for Nairobi (see Table 2), while their non-traffic sites or traffic samples collected in dusty Harmattan season had even lower levels and fractions (data not reproduced here). Reasons for these lower concentrations include longer sampling time periods (e.g., 24–48 h) that would integrate times of the day with potentially less traffic congestion, potentially longer distances to edge of roadways or greater heights (typically undefined in the other studies), as well as potentially different mixtures of vehicles and fuels used (also not discussed in most of the other papers). Higher minute and hourly concentrations were reported for heavily trafficked sites from a number of African cities from real-time aethalometer measurements (Doumbia et al., 2012). In Doumbia et al. (2012), the data were presented in a way that 11 h average concentrations could be extracted visually from graphs showing diurnal cycles in BC levels, resulting in two cities having 11 h averages similar to those measured in Nairobi. Dakar, Senegal had 11 h averages estimated from a graph that presented min and max diurnal cycles during the month of November 2008, resulting in approximate 11 h means that ranged from $\sim$10 to $\sim$50 $\mu g\,m^{-3}$ and Bamako, Mali had approximate 11 h geometric means of different days of the week from $\sim$10 to $\sim$30 $\mu g\,m^{-3}$, where the authors pointed to the high use of motorcycles including two-stroke motorcycles for Bamako (Doumbia et al., 2012).

4.1. Health and policy implications

Despite the small dataset, the results of this study imply high exposure to poor air quality for the large weekday population of pedestrians and shopkeepers in downtown Nairobi. The area contains officially designated locations for passenger pickup and drop-off by Matatus' and Long distance buses. It is also an area where affordable restaurants are available for low-income workers. Potentially exposed populations include low-income earners who have to walk along the busy roads daily in search of casual labor, such as the street hawkers, shop attendants/employees, the upcountry travelers, and shoppers. These pedestrians are typically dropped and picked by Matatus and buses in the area around the CBD areas where we sampled. Even though there are no studies showing a relationship between poor air quality and the national health budget in Kenya, studies and experience from developed countries imply a high cost in urban centers. $PM_{2.5}$ is known to be an important risk factor for premature mortality due to cardio-pulmonary diseases and lung cancer (Pope et al., 2002), and there is some evidence that BC and associated traffic-related pollutants may be especially dangerous (Janssen et al., 2003; Li et al., 2016). According to WHO (2014) urban air pollution was identified as one of the key cancer risk factors while Straif et al. (2014) reported 3.2 million deaths having occurred in 2010 due to cardiovascular disease and 0.2 million due to lung cancer as a result of air pollution (Straif et al., 2014; WHO, 2014).

Lung cancer risk is of particular concern for BC and related diesel exhaust components. The Clean Air Task Force (CATF, 2014) reported that exposure to diesel particulates represented one of the leading sources of excess cancer risk from air pollutants. Diesel combustion contributes the highest BC in urban aerosols (Seinfeld and Pandis, 1998), and BC measurements in urban areas are often used as a proxy for exposure to diesel emitted particles (Miguel et al., 1998; Fruin et al., 2004). Based on the exposure-response

function for lung cancer for ambient $PM_{2.5}$ reported by the global burden of disease study, the elevated BC levels measured at the curbside in the Nairobi CBD (30–53 $\mu g\ m^{-3}$) would suggest a substantial excess cancer risk for people working or living in the areas of the measurements sites in the CBD (Cohen et al., 2017).

There is concern that air pollution levels in Nairobi could rise further due to rapid urbanization and associated population increase and economic development, thus leading to increased private and public transport use and congestion. This is in the midst of poor understanding and appreciation of the dangers of air pollution within the policy maker community relevant to Nairobi, resulting in the overall lack of air quality monitoring, necessary infrastructure, and research funding. However, information from targetted research studies on air pollution sources and levels (e.g., van Vliet and Kinney, 2007; Gatari et al., 2009; Ye et al., 2009; Kinney et al., 2011; Gaita et al., 2014; Ngo et al., 2015; Egondi et al., 2016) is of critical importance to city planners and the Kenyan Government as they demarcate pedestrian paths, open-air markets, and shopping centers in highly congested areas. These studies, including the current one, offer a straightforward message to policy makers with regard to deteriorating air quality and potential human health implications. They also indirectly highlight the fact that sustainable mitigation and control strategies will require frequent and ongoing monitoring to understand temporal and spatial variations in air quality.

The high levels of air pollution we observed should be an important alert call to Kenyan policy makers to focus on means of mitigating poor air quality. Even while we await eventual studies relating air quality to human health in Kenya, the available research knowledge on the impacts of air pollution is adequate to support policy development on urban air pollution in Kenya. The Kenya National Environmental Management Authority has so far mainly focused on industrial emissions, whereas our study suggests that an important contributor to urban air pollution in Kenya is traffic, at least in dense urban core areas. Poor air quality can be a major factor in inhibiting sustainable economic growth, and can limit growth in tourism and foreign investment. We suggest that future policy developments should prioritize mitigation of poor air quality due to emissions from on-road vehicles, with a particular focus on diesel vehicles. Policy options may include enhanced fuel quality regulations, emission control technology standards, and enforceable inspection and maintenance requirements. While challenging in practice, such measures have the potential to achieve substantial benefits for air quality, health, and economic development in Nairobi.

Acknowledgements

We acknowledge the Volvo Research and Education Foundation for support. Additional support was provided by NIEHS Center Grant ES09089, and by International Science Programme of Sweden for capacity and infrastructure support at the host Institute in University of Nairobi, Kenya. The authors recognize the observed hard work and commitment of the field sampling campaign team.

References

Aboh, I.J.K., Henriksson, D., Laursen, J., Lundin, M., Ofosu, F.G., Pind, N., Lindgren, E.S., Wahnstrom, T., 2009. Identification of aerosol particle sources in semi-rural area of Kwabenya, near Accra, Ghana, by EDXRF techniques. X-Ray Spectrom 2009 (38), 348–353.

Abu-Allaban, M., Lowenthal, D.H., Gertler, A.W., Labib, M., 2007. Sources of PM10 and PM2.5 in Cairo's ambient air. Environ. Monit. Assess. 133 (1–3), 417–425.

Antonel, J., Chowdhury, Z., 2014. Measuring ambient particulate matter in three cities in Cameroon, Africa. Atmos. Environ. 95, 344–354.

Arku, R.E., Vallarino, J., Dionisio, K.L., Willis, R., Choi, H., Wilson, J.G., et al., 2008. Characterizing air pollution in two low-income neighborhoods in Accra, Ghana. Sci. Total Environ. 402 (2–3), 217–231.

Boman, J., Linden, J., Thorsson, S., Holmer, B., Eliasson, I., 2009. A tentative study of urban and suburban fine particles (PM2.5) collected in Ouagadougou, Burkina Faso. X-Ray Spectrom 38, 354–362.

Boman, J., Shaltout, A.A., Abozied, A.M., Hassan, S.K., 2013. On the elemental composition of $PM_{2.5}$ in central Cairo, Egypt. X-Ray Spectrom. http://dx.doi.org/10.1002/xrs.2464.

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.H., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. J. Geophys. Res.-Atmos. 109 (D14), 43.

Cadle, S.H., Groblicki, P.J., 1982. An Evaluation of Methods for the Determination of Organic and Elemental Carbon in Particulate Samples. Plenum Press, New York, pp. 89–109.

Cahill, T.A., Cahill, T.M., Barnes, D.E., Spada, N.J., Miller, R., 2011. Inorganic and organic aerosol downwind of California's Roseville Railyard. Aerosol Sci. Technol. 45, 1049–1059.

CATF, Clean Air Task Force, 2014. < http://www.catf.us/diesel/dieselhealth/faq.php?site=0#higher > (accessed on 18 April 2014).

Chitere, P.O., Kibua, N., 2011. Efforts to Improve Road Safety in Kenya: Achievements and Limitations of Reforms in the Matatu Industry. Institute of Policy Analysis and Research (IPAR), P.O. Box 45843-00100, Nairobi, Kenya. www.ipar.or.ke.

Chow, J.C., Watson, J.G., Crow, D., Lowenthal, D.H., Merrifield, T., 2001. Comparison of IMPROCE and NIOSH carbon measurements. Aerosol Sci. Tech. 34 (1), 23–34.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., et al., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389 (10082), 1907–1918.

Dionisio, K.L., Rooney, M.S., Arku, R.E., Friedman, A.B., Hughes, A.F., Vallarino, J., Agyei-Mensah, S., Spengler, J.D., Ezzati, M., 2010. Within-neighborhood patterns and sources of particle pollution: mobile monitoring and geographic information system analysis in four communities in Accra, Ghana. Environ. Health Perspect. 118 (5), 607–613.

Dockery, D.W., Pope, C.A., Xu, X., Sprengler, I.D., 1993. An association between air pollution and mortality in six U.S., Cities. New Engl. J. Med. 329, 1573–1759.

Doumbia, E.H.T., Liousse, C., Galy-Lacaux, C., Ndiaye, S.A., Diop, B., Ouafo, M., Assamoi, E.M., Gardrat, E., Castera, P., Rosset, R., Akpo, A., Sigha, L., 2012. Real time black carbon measurements in West and Central Africa urban sites. Atmos. Environ. 54, 529–537.

Egondi, T., Muindi, K., Kyobutungi, C., Gatari, M., Rocklöv, J., 2016. Measuring exposure levels of inhalable airborne particles (PM2.5) in two socially deprived areas of Nairobi, Kenya. Environ. Res. 148, 500–506.

Fruin, S.A., Winer, A.M., Rodes, C.E., 2004. Black carbon concentrations in California vehicles and estimation of in vehicle diesel exhaust particulate matter exposures. Atmos. Envirion. 38 (25), 4123–4133.

Gaita, S.M., Boman, J., Gatari, M.J., Pettersson, J.B.C., Janhäll, S., 2014. Source apportionment and seasonal variation of PM2.5 in a Sub-Saharan African city: Nairobi, Kenya. Atmos. Chem. Phys. 14, 9977–9991.

Gatari, M.J., Boman, J., 2003. Black carbon and total carbon measurements at urban and rural sites in Kenya, East Africa. Atmos. Environ. 37 (2003), 1149–1154.

Gatari, M.J., Boman, J., Wagner, A., 2009. Characterization of aerosol particles at an industrial background site in Nairobi, Kenya. X-Ray Spectrom 38, 97 97-44.
Gatari, M., Boman, J., Hays, M., Wagner, A., 2010. Black carbon concentration at an urban background site: an indicator of Traffic patterns in Nairobi, Kenya. In: Proceedings of the International Aerosol conference (IAC) 2010, Helsinki, Finland, August 2010.
Hinds, W.C., 1999. Aerosol Technology: Properties, Behaviour and Measurement of Airborne Particles. John Wiley & Sons, New York.
IARC, International Agency for Research on Cancer, 2013. Air Pollution and Cancer. IARC Scientific Publication No. 161. Lyon.
Janssen, N.A.H., Brunekreef, B., van Vliet, P., Aarts, F., Meliefste, K., Harssema, H., Fischer, P., 2003. The relationship between air pollution from heavy traffic and allergic sensitization, bronchial hyperresponsiveness, and respiratory symptoms in Dutch schoolchildren. EHP 111 (12), 1512–1518.
Kinney, P.K., Gatari, M.G., Volavka-Close, N., Ngo, N., Ndiba, P.K., Law, A., Gachanja, A., Gaita, S.M., Chillrud, S.N., Sclar, E., 2011. Traffic impacts on $PM_{2.5}$ air quality in Nairobi, Kenya. Environ. Sci. Policy 14, 369–378.
KNBS, Kenya Bureau of Statisticse, 2007, 2011. Kenya Economic Survey Report. Ministry Planning, Government of Kenya, Nairobi, Kenya.
Kocbach, A., Li, Y., Yttri, K.E., Cassee, F.R., Schwarze, P.E., Namork, E., 2006. Physiochemical characterisation of combustion particles from vehicle exhaust and residential wood smoke. Part. Fibre Toxicol. 3, 1–10.
Korir, A., Okerosi, N., Ronoh, V., Mutuma, G., Parkin, D.M., Gathere, S., 2015. Incidence of cancer in Nairobi, Kenya (2004–2008). Int. J. Cancer 137, 2053–2059.
Straif, K., Cohen, A., Samet, J., 2014. Air Pollution and Cancer. Publication No, IARC Scientific, pp. 161.
Lawless, P.A., Rodes, C.E., Ensor, D.S., 2004. Multiwavelength absorbance of filter deposits for determination of environmental tobacco smoke and black carbon. Atmos. Environ. 38 (21), 3373–3383.
Lena, T.S., Ochieng, V., Carter, M., Holguín-Veras, J., Kinney, P.L., 2002. Elemental carbon and $PM_{2.5}$ levels in an urban community heavily impacted by truck traffic. Environ. Health Perspect. 110, 1009–1015.
Li, Y., Henze, D.K., Jack, D., Henderson, B.H., Kinney, P.L., 2016. Assessing public health burden associated with exposure to ambient black carbon in the United States. Sci. Total Environ. 539, 515–525.
Liousse, C., Assamoi, E., Criqui, P., Granier, C., Rosset, R., 2014. Explosive growth in African combustion emissions from 2005 to 2030. Environ. Res. Lett. 9 (3), 1–10.
McCormick, D., Mitullah, W., Chitere, P., Orero, R., Ommeh, M., 2016. Matatu business strategies in Nairobi. In: Behrens, R., McCormick, D., Mfinanga, D. (Eds.), Paratransit in African Cities. Routledge, New York, pp. 125–154.
Miguel, A.H., Kirchstetter, T.W., Harley, R.A., Hering, S.V., 1998. On-road emissions of particulate polycyclid aromatic hydrocarbons and black carbon from gasoline and diesel vehicles. Environ. Sci. Technol. 32 (4), 450–455.
Mkoma, S.L., Chi, X., Maenhaut, W., 2010. Characteristics of carbonaceous aerosols in ambient PM10 and PM2.5 particles in Dar es Salaam, Tanzania. Sci. Total Environ. 408 (6), 1308–1314.
Ngo, N.S., Gatari, M., Yan, B., Chillrud, S.N., Bouhamam, K., Kinney, P.L., 2015. Occupational exposure to roadway emissions and inside informal settlements in sub-Saharan Africa: a pilot study in Nairobi, Kenya. Atmos. Environ. 111, 179–184.
NIOSH, 1999. National Institute for Occupational Safety and Health Method 5040, Elemental Carbon (Diesel Particulate), NIOSH Manual of Analytical Methods (NMAM), fourth ed., Issue 3.
Orero, R., Mccormick, D., Mitullah, W., Chitere, P., Ommeh, M., 2012. Assessing progress with the implementation of the public transport policy in Kenya. In: Proceedings (ISBN: 978-1-920017-53-8 Pretoria) of 31st Southern African Transport Conference (SATC 2012), 9–12 July 2012.
Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. J. Am. Med. Assoc. 287 (9), 1132–1141.
Pope, C.A., Ezzati, M., Dockery, D.W., 2009. Fine-particulate air pollution and life expectancy in the United States. NEJM 360, 376–386.
Seinfeld, J.H., Pandis, S.N., 1998. Atmospheric Chemistry and Physics, John Wiley & Sons, INC., New York, pp. 700–714.
Steiner, D., Burtchner, H., Grass, H., 1992. Structure and disposition of particles from ignition engine. Atmos. Environ. 26, 997–1003.
Streets, D.G., Bond, T.C., Lee, T., Jang, C., 2004. On the future of carbonaceous aerosol emissions. J. Geophys. Res.-Atmos. 109, D24212. 19 pp.
USEPA, 2012. Report to Congress on Black Carbon. EPA-450/R-12-001, March 2012, pp. 351.
van Vliet, E.D.S., Kinney, P.L., 2007. Impacts of roadway emissions on urban particulate matter concentrations in sub-Saharan Africa: new evidence from Nairobi, Kenya. Environ. Res. Lett. 2, 045028. 5 pp. http://dx.doi.org/10.1088/1748-9326/2/4/045028.
Wang, R., Tao, S., Shen, H., Huang, Y., Chen, H., Balkanski, Y., Boucher, O., Ciais, P., Shen, G., Li, W., Zhang, Y., Chen, Y., Lin, N., Su, S., Li, B., Liu, J., Liu, W., 2014. Trend in global black carbon emissions from 1960 to 2007. Environ. Sci. Technol. 48 (12), 6780–6787.
WHO, 2014. Ambient (Outdoor) Air Quality and Health. Fact Sheet Number 313.
Yan, B., Kennedy, D., Miller, R.L., Cowin, J.P., Jung, K., Perzanowiski, M., Balletta, M., Perera, F.P., Kinney, P.L., Chillrud, S.N., 2011. Validating a nondestructive optical method for apportioning colored particulate matter into black carbon and additional components. Atmos. Environ. http://dx.doi.org/10.1016/j.atmosenv.2011.01.044.
Ye, Y., Zulu, E., Mutisya, M., Orindi, B., Emina, J., Kyobutungi, C., 2009. Seasonal pattern of pneumonia mortality among under-five children in Nairobi's informal settlements. Am. J. Trop. Med. Hyg. 81 (5), 770–775.
Zhou, Z., Dionisio, K.L., Verissimo, T.G., Kerr, A.S., Coull, B., Arku, R.E., Koutrakis, P., Spengler, J.D., Hughes, A.F., Vallarino, J., 2013. Chemical composition and sources of particle pollution in affluent and poor neighborhoods oa Acrra, Ghana. Environ. Res. Lett. 8, 044025 9 pp.